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Underestimating the global land squeeze:

How this challenge is misunderstood and how investors can help

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By Santander

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Searchinger's work combines ecology, agronomy and economics to analyze the challenge of how to feed a growing world population while reducing deforestation and greenhouse gas emissions from agriculture. His publications include multiple papers in Science and Nature addressing bioenergy, nitrogen pollution and the greenhouse implications of agriculture and land use change. He was the lead author of a comprehensive, detailed report describing these challenges and potential solutions called Creating a Sustainable Food Future, which was published in 2019 by WRI, the World Bank and the United Nations.

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Introduction

Does the world face a daunting land use challenge to simultaneously meet the world's growing demands for food while preserving natural lands for carbon and biodiversity? Or does the world have so much unused land that it can devote vast stretches of the world's land to bioenergy, immediately start to reforest hundreds of millions of hectares of grasslands, and shift to agricultural practices that use fewer inputs but produce less food per hectare?

A conscientious reader of scientific articles, official reports or just good journalism could believe alternatively that the world has a shortage or surplus of land. Unfortunately, the first position is more accurate: the world faces a "global land squeeze" as it simultaneously needs to produce more food and fiber while leaving more land to nature. Mathematically, the only ways to achieve these goals are to produce more food on the same land or to reduce the level of growth in demand for land-intensive products. In practice, both are required. Investors in the food system should be guided by these principles of "produce and reduce." This paper discusses how and why directing investment properly requires reforming the greenhouse gas accounting standards companies use so that they recognize the carbon opportunity cost of land. Investments are also needed to increase land use efficiency, above all both to develop alternatives to beef and to increase the efficiency of beef production, and to pursue critical innovations.

02

The global land use situation today

As of today, people have converted roughly one half of the world's vegetated land to agriculture and have harvested and otherwise manipulated at least three quarters, and likely even more, of the world's remaining forests[1]. Because doing so releases much of the vast carbon stored in vegetation and soils, these changes are responsible for at least one quarter of the carbon dioxide people have added to the atmosphere. These changes also explain the vast majority of the world's losses of wildlife and biodiversity. Along with energy use, agriculture and forestry represent the primary human drivers of environmental degradation on a global scale.

The basic reason for this harm is not malevolent agricultural or forestry practices; it is the extensive land-use required to feed and provide wood to eight billion people. Without large agricultural advances, the world would have converted even more forests and savannas. The global population would probably also be smaller, which might sound attractive, but the cause would have been more periodic famine and child malnutrition.

This conversion of native habitats for agriculture is occurring at expanding rates. Conversion of forest to pasture is the major direct source of agricultural conversion[2]. A good satellite study of global cropland change, which became available only two years ago, found annual cropland expanding recently at a net rate of 10 million hectares per year[3]. If this trend continues from 2020 to 2050, people will clear an additional area the size of India (roughly 300 million hectares).

Because the global population is on a path toward nearly 10 billion people, and rising incomes are supporting more consumption of land-intensive foods, such as meat and milk, most modelers also project largescale agricultural expansion[4]. Modeling for the World Resources Institute/World Bank/UN report *Creating a Sustainable Food Future* highlighted how the level of expansion heavily depends on increased yields per hectare of both crops and meat and milk[5]. If regional crop yields continued to grow at similar rates since the 1960's, the model projected cropland would expand by 200 million hectares. If yields grew at the slower rate from 1989 to 2008, cropland would grow by 300 million hectares. And if the world yields would not grow at all, the world would expand cropland by more than 1 billion hectares, and pasture by billions of hectares more.

1 References for paper otherwise not cited can be found in the report, Searchinger et al. (2023). *The Global Land Squeeze: Managing the World's Growing Competition For Land*. World Resources Institute.

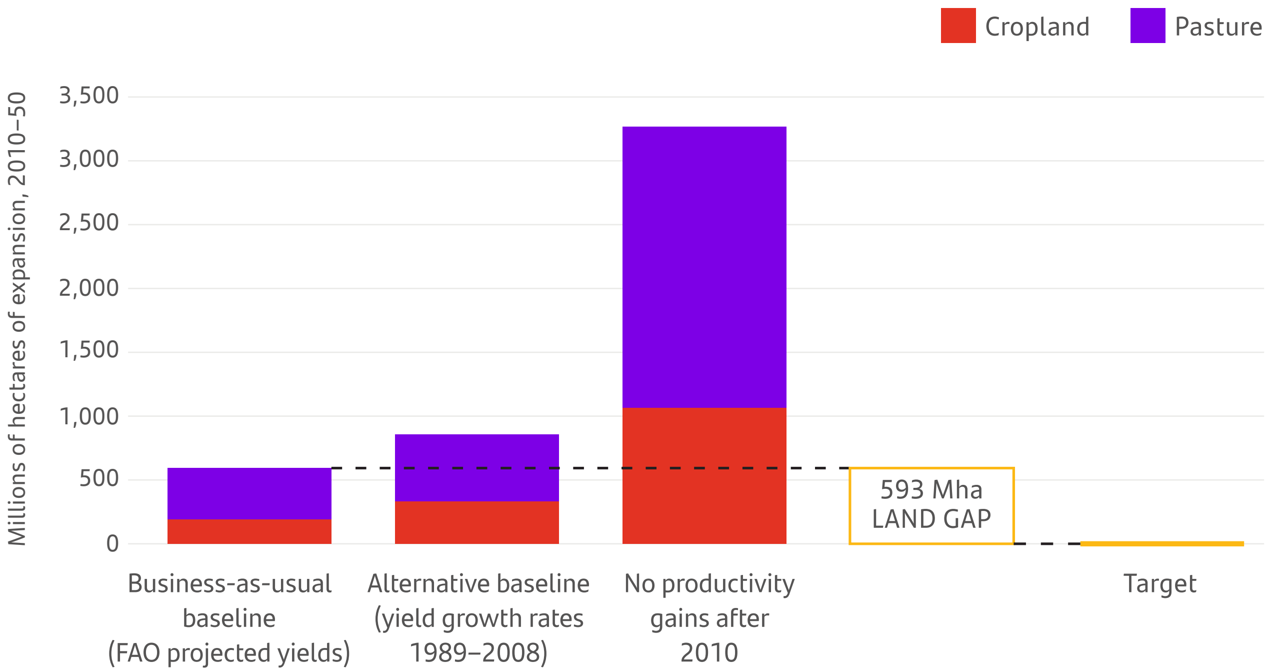
2 Weisse and Goldman (2021)

3 Potapov et al. (2021)

4 Schmitz et al. (2014)

5 Searchinger et al. (2019)

Figure 1: Increases in Agricultural Land Likely Required in 2050 Compared to 2010



Note: "Cropland" increase includes a 20 Mha increase in aquaculture ponds under the two projected baselines and a 24 Mha increse in the "no productivity gains after 2010" projection.

Source: Globagri model in Creating a Sustainable Food Future

The first column shows projected agricultural expansion based on yield gains that roughly track historic averages. The second shows projected expansion based on yield gains in a recent 20- year period. And the third column shows projected expansion with the same yields and livestock efficiency as in 2010. This scenario would destroy most of the remaining forests and wetter savannas left in the temperate zones and tropics.

This likely expansion contrasts with virtually all feasible paths for stabilizing the climate in accordance with the Paris Agreement. They require not just stabilizing but reducing agricultural land by 2050[6]. Restoring habitat on some agricultural lands is also necessary to help avoid a massive extinction of species likely to occur with climate change[7].

6 Rogelj et al. (2018), Sanderson, O'Neill, and Tebaldi (2016)

7 IPBES (2019)

03

Why this land squeeze is often underestimated

Despite basic arithmetic that requires higher yields and reduced demands for land, much academic work and policy recommends behaviors that require even more land:

- Numerous research papers and government policies are promoting the use of bioenergy, greatly increasing the competition for land. The global diversion of grain to biofuels in the U.S. and Europe alone, after accounting for by-products, is twice the grain exported by Ukrain[8] . Many climate strategies are calling for a quantity of bioenergy that would require burning an amount of biomass equal to all the world's crops, wood and forages[9]. If even one quarter of future aviation fuels come from vegetable oil, the world would have to double production of vegetable oil (author's calculations), although existing expansion is already driving tropical deforestation[10].

- Some experts advocate "regenerative agriculture" as the means of reducing agricultural greenhouse gas emissions. Exactly what constitutes regenerative agriculture is vague, but there are calls for converting crops to grazing to sequester carbon in soils and to increase organic food production, regardless of far lower food production[11]. Some voices call Kernza, a perennial wheat variety, a solution to climate change despite its low yield although that would require 500 million more hectares of global cropland to produce a comparable quantity of wheat[12].

- Certain research also suggests that the world can today reforest hundreds of millions of hectares of land for climate purposes[13], or plant extensive trees on cropland[14]. This recommendation occurs without any precondition that the world reduce its need for agricultural land either through yield gains or demand reductions.

8 Searchinger et al. (2022)
9 Searchinger, Beringer, and Strong (2017)
10 Weisse and Goldman (2021)
11 Thorbecke and Dettling (2019), Stanley et al. (2018), Fuchs, Brown, and Rounsevell (2020)
12 Kaplan (2021)
13 Bastin et al. (2019), Griscom (2017)
14 Chapman et al. (2020), Roe et al. (2021)

There are at least five inaccurate assumptions that support this impression of an abundance of surplus land.

01 Bioenergy and treating land as "free"

The most fundamental error arises from climate accounting systems that in effect treat the uses of existing agricultural land as "free": free in the sense that diverting land to another use has no climate cost. This is the error that has frequently driven bioenergy subsidies and mandates.

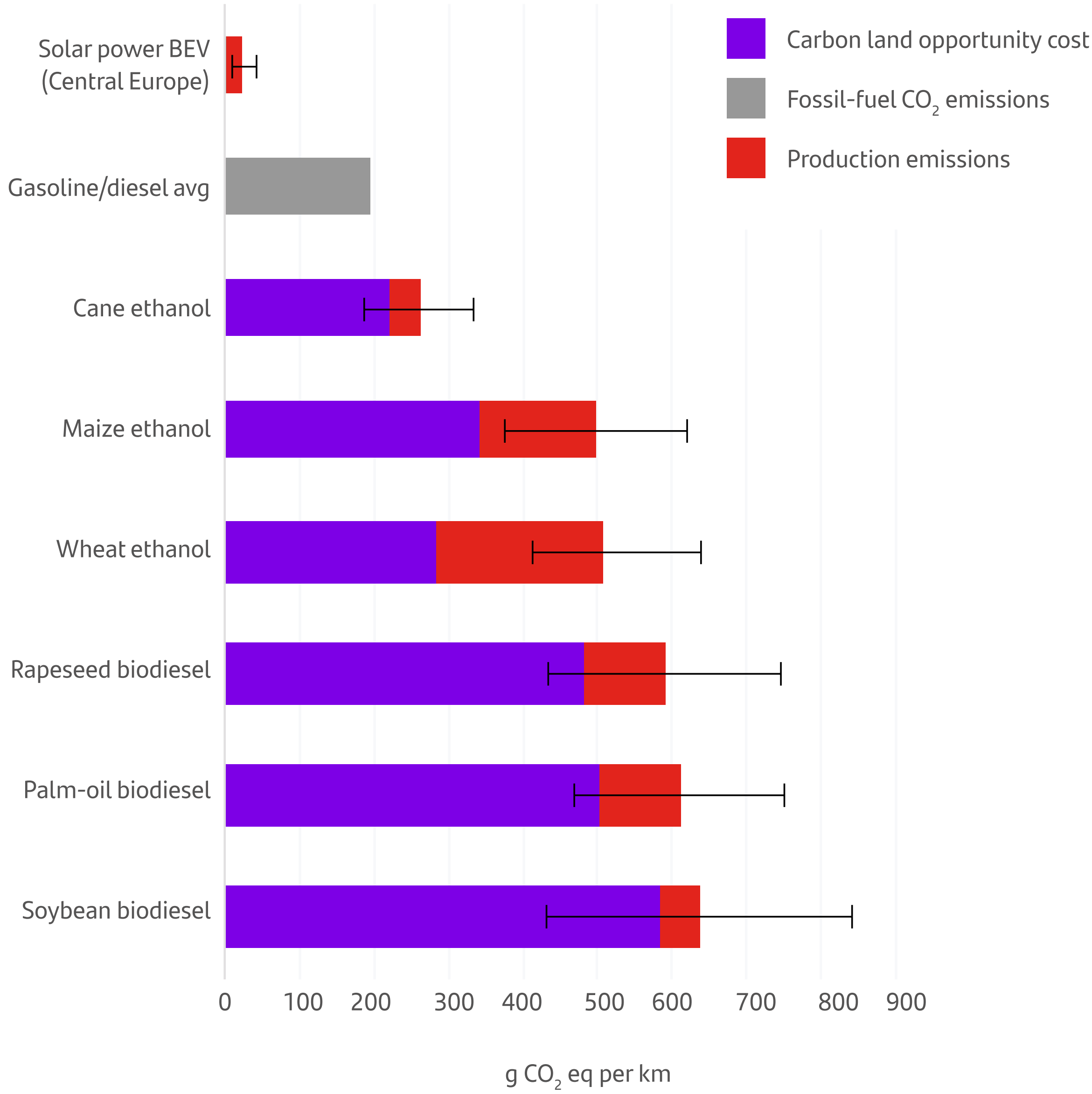
When biomass (dead plants or other formerly living material) is burned for energy, it releases carbon dioxide. Because of the nature of its chemical bonds, bioenergy in fact must directly release more carbon for each unit of energy than burning oil or natural gas and generally even more than coal. Why is it commonly thought that substituting fossil fuels with bioenergy would lead to a reduction in greenhouse gas emissions? The answer lies in the idea that biomass is carbon neutral, because it is just recycling carbon absorbed by plant growth. In this accounting, the carbon emitted by burning biomass is not counted.

The problem with this accounting is that it takes land to grow plants. And if this land is used to grow plants for bioenergy, it is not being used to grow plants for other human needs. These needs can vary from producing food, to storing carbon and providing biodiversity in native vegetation, to sequestering more carbon through reforestation, even to providing energy from photovoltaics. Using land for biofuels therefore has a real climate opportunity cost by foregoing these other uses.

Any comparison makes clear that this opportunity cost is high.

First, and most obviously, in a context where agricultural land is expanding, the best use of existing agricultural land, even for the climate, is typically to produce food to avoid the carbon cost of clearing new land for food production. The most effective approach to assessing the trade-offs involves a straightforward comparison: measure the average carbon emissions generated in the cultivation of crops designated for biofuel production and juxtapose this against the avoided petrol or emissions by replacing petrol or diesel with biofuels. Dividing this land use cost over 30 years is then a way of determining the net effect on emissions over this period. The result, as shown in **Figure 2**, is that ethanol from corn or wheat typically has two times the carbon cost of gasoline, and biodiesel from vegetable oils roughly three-times the carbon cost.

Figure 2: Carbon Costs of Different Fuel Sources



Source: Searchinger et al. (2018)

Second, clearing native habitats to make way for biofuel crops usually results in a net increase in carbon emissions, outweighing any emissions savings gained from replacing fossil fuels[15]. Moreover, allowing surplus agricultural land to revert to its natural forested state, should such land be available, would nearly always offer more substantial climate benefits than utilizing it for biofuel production[16]. If biofuels from fast-growing grasses can achieve extremely high yields in the future, they might achieve more greenhouse gas reductions than reforestation, but even then, the percentage reduction will be far from 100%. The world would therefore be better off replacing fossil fuels another way and reforesting the land.

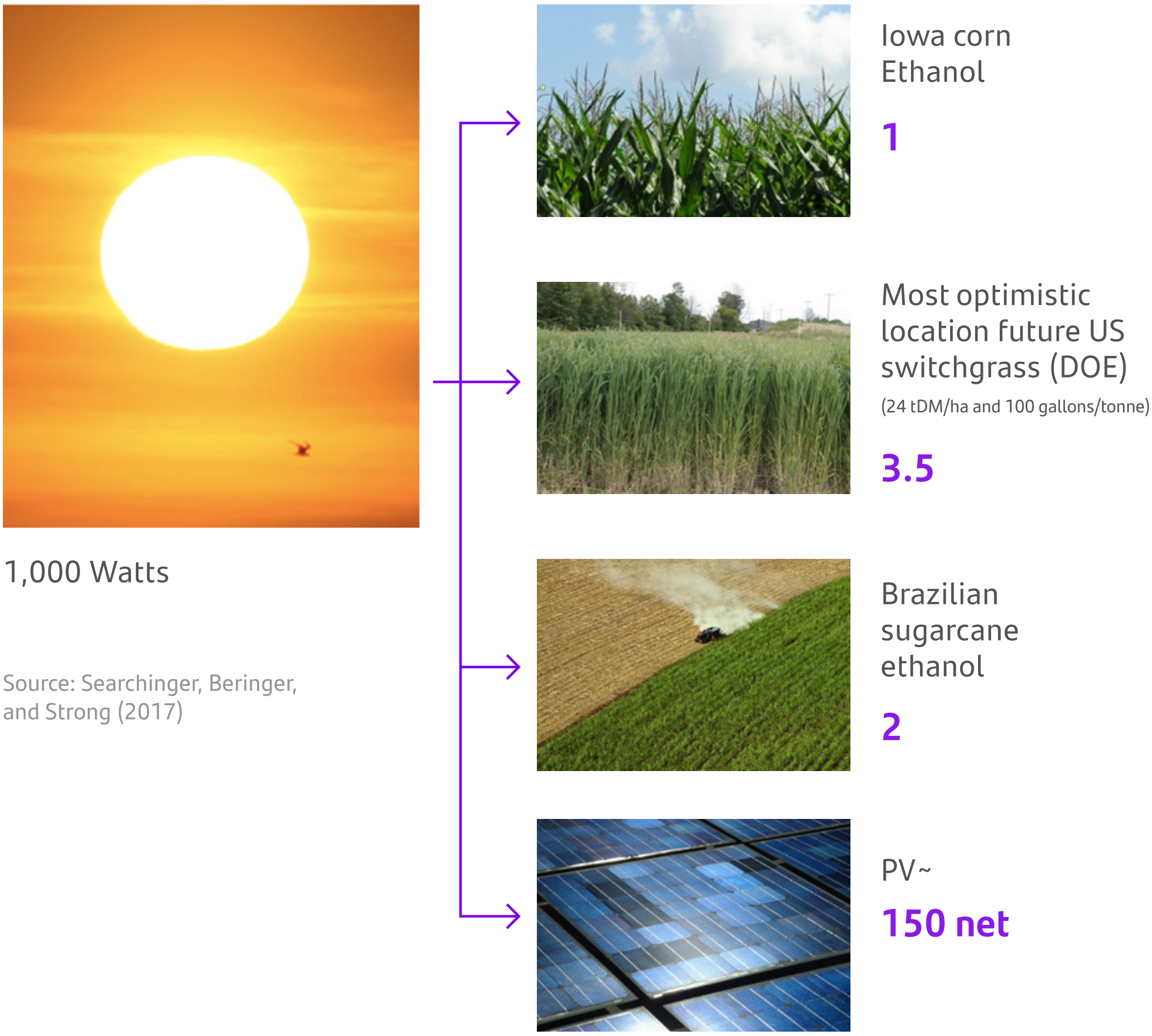
Third, it is increasingly likely that a portion of agricultural land will need to be allocated for photovoltaic (PV) solar energy installations. Biofuels represent an inefficient utilization of land for energy production. Even under optimal agricultural conditions, biofuels generate a net energy yield of merely 1 or 2 joules for every 1,000 joules of solar radiation received. In contrast, contemporary photovoltaic systems can produce around 150 joules on a net basis, as indicated in **Figure 3**[17]. Furthermore, due to the approximately three-fold higher efficiency of electric engines compared to conventional internal combustion engines, as well as the greater efficiency of heat pumps over fossil-fuel heating sources, the effective energy output per hectare from PV installations escalates to nearly 300 times that of bioenergy.

15 Searchinger et al. (2015); Evans et al. (2015)

16 Searchinger et al. (2015); Evans et al. (2015)

17 Searchinger, Beringer, and Strong (2017)

Figure 3: Solar conversion and land use efficiencies of biofuels are much lower than photovoltaics



Source: Searchinger, Beringer, and Strong (2017)

02 Treating pastures as “free”

A well-cited paper in the prominent journal Science[18] claimed the world had the potential to reforest roughly one billion hectares of land even after excluding agricultural areas from lands eligible for reforestation. This area of claimed reforestation potential is greater than the Continental U.S. But this analysis did not actually exclude agricultural areas. It only excluded cropland not pasture. The paper that coined the term “natural climate solutions” also relies on reforesting large areas of wetter pasture[19]. In effect, these papers identified for reforestation the roughly one billion hectares of pasture that people have carved out of the world’s native forests, including much of Europe, the eastern U.S., and Brazil. These are also the most productive pastures in the world. Although some poorly managed, highly sloped pasture could be reforested today, this land in general would only become available after highly successful efforts to reduce consumption of beef and to produce more on the same land.

03 Failing to properly communicate land use competition when reporting model results

Another major issue is that results are often presented in ways that imply the land use challenge is automatically met. The world in the past increased yields of crop or livestock on a continuous trend, and if modelers assume no future yield gains, they can appear to be exaggerating future harm. But if modelers assume large, ongoing yield gains, the projected land use change will be much lower or even non-existent. Readers can easily gain the impression that these yield gains are automatic and therefore not something that requires affirmative action.

In reality, no yield gains are automatic. In the past, yield gains resulted from extensive private and public efforts, major technological changes, and infrastructure. Many of the driving factors in the past are no longer possible in the future in most of the world because of high environmental costs and extensive existing use, such as introducing synthetic fertilizer to most of the world and doubling irrigation. It will take major public and private policy initiatives, and much greater reliance on “farming smarter”, to achieve the necessary rate of yield gains in the future.

18 Bastin et al. (2019)

19 Griscom (2017)

04 Land shifting, outsourcing, and improperly claiming surplus land

In the U.S., there is an expression from baseball that a rich child was born on third base and thought he had hit a triple. For most of the world, the equivalent is of a person born into the second half of a football game with a 3-0 lead who thought he was Lionel Messi. These expressions accurately characterize the land use situation faced by the temperate world.

Europe, the U.S. and China cleared so much land for agriculture in the past that agricultural land has been declining for some decades. (Some of this reduction was due to use of cars and tractors to replace horses, which required vast areas of oats and hay to feed). With stable or even declining populations, so long as yields grow, less agricultural land is needed. In addition, Europe and China have outsourced much of their food production to other countries, freeing up land in Europe[20].

Both governments and many individuals want to think this reduced need for agricultural land gives them free land to use in some other way. For example, although Europe already uses one hectare of cropland abroad for its own agricultural consumption for each four hectares in Europe, its new Fit for 55 climate plan contemplates diverting roughly one fifth of Europe's cropland to energy crops[21]. But this land is not free. To meet global demands, this land is needed to supply food. And if no longer economical for food, it is needed for reforestation, to sequester carbon and provide some biodiversity, to help balance out the carbon and biodiversity lost from ongoing land conversion abroad.

Europe has by law now prohibited the import of several major agricultural products produced on newly deforested land, including soybeans, beef, and coffee. That is commendable. But because of false ideas of surplus land, Europe's climate plan contemplates even more reliance on existing cropland abroad, which is now feeding other people, while claiming no responsibility for the resulting deforestation to replace the food for others.

20 Pendrill et al. (2019), Searchinger et al. (2022)

21 Searchinger et al. (2022)

05 Claiming one use of land is free because another will decrease.

Many papers or advocates of specific causes claim that their preferred use of additional land does not have additional climate costs so long as others reduce their land use. For example, some European experts are calling for a broad shift to less intensive agricultural methods but claim that will not have land use costs because Europe can also dramatically reduce its consumption of meat and milk[22]. The UK Committee on Climate Change claimed land can be available for bioenergy so long as people dramatically change their meat consumption and also reduce food losses and waste[23].

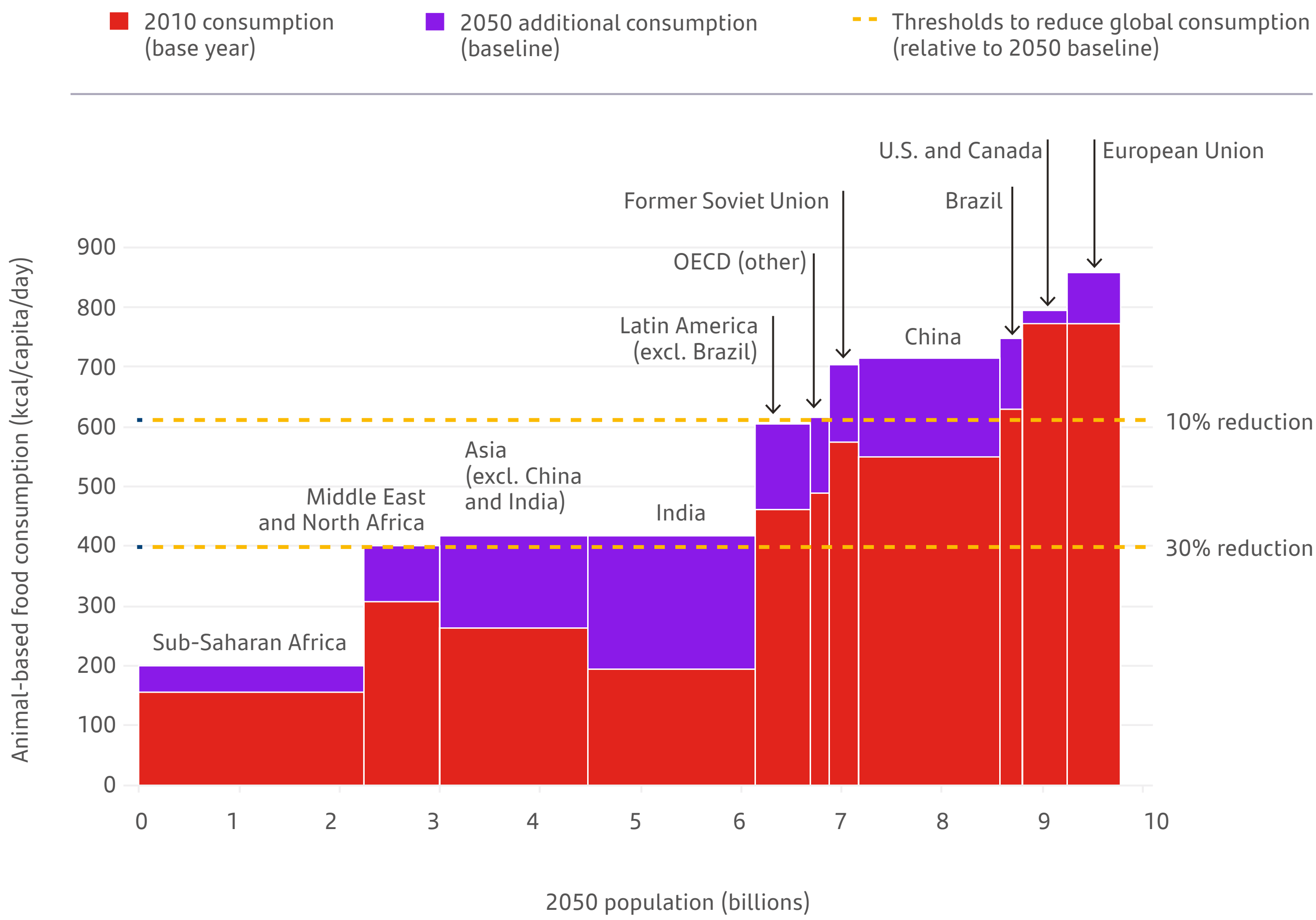
These claims suffer from factual and logical limitations. As demonstrated in **Figure 4**, by the year 2050, over six billion people are projected to reside in countries where the consumption of meat, milk, and fish is approximately one-fourth that of Western populations. Given the minimal levels of meat and milk consumption in these regions and the likely increases, reductions by individuals in the West are imperative simply to stabilize global land use.

And logically, the world needs to find every way it can to save land just to produce food or to restore native habitats and their carbon. This means that to the extent Westerners can reduce their land use requirements, this land is still needed for these other purposes and does not create room to create yet additional demands for land.

22 Aubert, Schoob, and Poux (2019)

23 UK Committee on Climate Change (2020)

Figure 4: Reduced meat consumption in the West is needed to create room just for others to eat a little more



In this graphic, the horizontal axis shows the population for each region or country, and the vertical axis the per person consumption of meat, milk and fish in calories. The red shows consumption in 2010, and the purple adds projections by the UN Food and Agriculture Organization of increased consumption in 2050. The 10% and 30% reduction lines show the maximum level of food consumption each country or region can have if the world is to reduce consumption of animal products by these percentages compared to projected 2050 levels. The graph shows that more than 6 billion people live in countries or regions where average consumption per person is only around 200 kcal per day compared to Western consumption of roughly 800 kcal.

Source: Searchinger et al. (2019)

04

Key measures to guide investment toward produce & reduce

Investment has a key role to play to "produce and reduce." Directing investment properly requires first getting the incentives to investors right. A few examples then highlight some priority investments.

First, get carbon accounting right

Flawed carbon accounting rules, including those guiding investors, are the fundamental reason for the misguided trajectory of land use policy and research. The first rule to guiding investment well is to properly factor in the true climate significance of using more or less land.

The basic problem, as discussed for biofuels, is that climate accounting is treating existing agricultural land as "free." If agricultural products are generated on newly cleared land, typical rules provide that companies must be responsible for emissions of the lost carbon. But no matter how much existing agricultural land is used, or how much land-intensive products are consumed, there is no climate cost assigned to this use. As a result, companies can decrease yields, divert land from food production, or increase their use of land-intensive products, and accounting rules will assign no emissions. One way to summarize the rules is that they potentially assign climate costs based on where companies obtain their agricultural products but assign no climate costs based on how much land companies use. That also means companies have no incentive to use less land.

What should the rule be? Imagine there were only one agricultural company in the world producing food and distributing it, and the global demand for food grows by 1% per year. If yields grow by 1% per year, there will be no net expansion of agricultural land. But if yields only grow by 0.5% per year, agricultural land will expand by 0.5% per year. That does not sound like much, but that would be roughly 25 million hectares of land. Conversely, if yields grow by 1.5% per year, agricultural land would contract by roughly 25 million hectares, allowing that much reforestation. The same math applies to the companies collectively. For this reason, the degree of progress companies make in increasing yields becomes a direct measure of their contribution to increasing or avoiding carbon emissions from clearing land.

When decreasing or increasing food production, one simple way to measure this effect is to measure the carbon emissions that would be lost on average when converting new cropland to produce the food elsewhere. When food production on a hectare increases, it saves these costs. When food production decreases, it increases these costs. This cost of diverting land can be thought of its carbon opportunity cost[24].

24 Searchinger et al. (2018)

Using this metric, companies seeking to reduce their emissions should develop targets to increase land use efficiency at a sufficient rate to avoid contributing to land use change. For companies that produce food, that basically requires increasing yields. For companies that interact with consumers, encouraging those consumers to switch to less land-intensive products should also qualify, such as shifting from meat-based hamburgers to plant-based "hamburgers." If companies exceed their targets, they are making more land available to meet other food needs and should be rewarded for reduced emissions from land use change.

Pursue Key Opportunities to Reduce

Two key opportunities can guide investments to "reduce" human demands for land-intensive products: invest in alternatives to bioenergy and beef.

Phase biofuels out not up

There are different ways of estimating areas devoted to biofuels, but using one estimate by a major biofuels' supporter, the world devoted 84 million hectares of cropland to biofuels in 2021[25]. Nearly all of that land use has emerged in the last 20 years, during a period when total net expansion of annual and permanent cropland was probably around 160 million hectares[26]. There is no evidence that increased biofuel production has spurred crop yields beyond trend lines. This means that the expansion of biofuels probably explains roughly half of the cropland expansion and therefore much of the world's deforestation.

As explained above, biofuels that require land, rather than use wastes, represent a peculiarly inefficient use of land. They should be phased out, particularly because of the far higher efficiency of solar power.

25 Oil & Fats International, Only 8% of global crop land used for biofuels (January 31, 2023) https://www.ofimagazine.com/news/only-8-of-global-crop-land-used-for-biofuels

26 Potapov et al. (2021) found net expansion of annual cropland between 102 and 125 million hectares from 2003-2019 using two different method. Using this average rate over 20 years, would estimate net expansion of 143 Mha. During this time, FAO data would suggest expansion of another 20 Mha of permanent cropland during this time for a total of 163 Mha. All these figure have uncertainties and so we use round figures in the main text.

Invest in alternatives to beef

The world's beef production is responsible for nearly half of the carbon lost from the world's agricultural land but generates only around 3% of the calories[27]. Roughly 40% of the world's pasture was historically forested or heavily wooded[28], an area nearly the size of the world's total cropland. This wetter pasture provides most of the world's beef. When vegetarian and vegan diets are analyzed, the vast majority of the land and climate savings result from the reduced consumption of beef[29].

Holding down the global growth in consumption of beef should be feasible. Today, the average person in Western Europe or the U.S. eats one third less beef than the average person in the mid-1970s[30]. Per capita consumption of beef has started to decline even in Brazil.

One way to promote alternatives is to support plant-based meats. Key to their success is having products that match the taste and other pleasures of eating beef at the same or less cost. Among existing alternatives, tests by the Good Food Institute have found only one brand today generates a product that matches eating a hamburger, and its sales continue to do better than competitors although its price remains higher than real beef. This whole field is a prime area for beneficial investment to bring more comparable products to market at a price less than that of beef.

Key produce priorities

All yield gains and all increases in the efficiencies of feeding livestock help reduce global land use requirements. Crop breeding, which can take advantage of the enormous improvements in microbiology in the last two decades, could likely play a major role particularly if provided with the research funding necessary. In much of the world – and despite wide-ranging estimates due to different estimation methods -- there are also large "yield gaps". These are the differences between the livestock and crop yields farmers actually achieve and those possible just by making use of known management options. Two are worth special emphasis.

27 Searchinger et al. (2019)
28 Searchinger et al. (2018)
29 Searchinger et al. (2019)
30 Searchinger et al. (2019)

Improve pasture output in Latin America

The wetter grazing land of Latin America provides by far the world's largest reservoir of underutilized land that could help the world meet rising demands for multiple products if properly utilized. Between 400–500 million hectares of land in Latin America are devoted to pasture, and around three quarters of this grazing land is wet enough either to provide much higher agricultural production or to restore as forests or other valuable habitats[31]. The vast majority of this land is poorly grazed, typically supporting less than one animal per hectare and on average producing only around 50 kg of beef per hectare[32]. In Brazil, the number of cattle per hectare is less than one; in Colombia it is only slightly more than half.

With rising global demand for beef, cattle expansion is the largest, direct source of deforestation, primarily in Latin America[33]. At the same time, much of this land is suitable to provide other crops, such as soybeans[34].

Established ways can increase the output of beef on hundreds of millions of hectares at least three- or four-fold. Basic management options include liming and fertilizing the soil, replanting productive grasses when necessary, and rotating cattle rapidly among different pastures while supplying adequate water. Devoting part of a farm to a high-yielding grass can supply a feed during the dry season to keep cattle from losing weight. Better farms are bringing cattle into feeding areas for a short period every day to consume some grain concentrates. Some of the most advanced farming operations use intensive silvopastoral systems that include nitrogen-fixing shrubs that both supply the nitrogen for the grasses and themselves provide a high-protein feed, as well as a layer of trees to keep moisture in and to provide shade.

Not all wetter pasture will be suitable for these kinds of improvements, including those on steep slopes. But there are rising demands on this land: including rising global demand for beef, for other crops such as soybeans, for wood from plantations and for natural reforestation. As a result, any land-saving solution for the planet probably requires at least tripling the output per hectare on 200 million hectares of poor grazing land in Latin America[35]. At an investment cost of around $2,000 per hectare, that probably means a need for something like $400 billion in investment over the next 20 years.

31 Searchinger et al. (2019)

32 Searchinger et al. (2019)

33 Weisse and Goldman (2021)

34 Strassburg et al. (2014), Gibbs et al. (2015)

35 Searchinger et al. (2019)

Many farms are already using these improvements, so their use can be profitable. The Brazilian government has provided subsidized loans for these kinds of improvements as part of its climate-strategy, but not all farmers are able or willing to take these loans. Additional business models are required. One interesting strategy pioneered by a small company takes over a farm's management for around ten years, improves it, pays the farmer the regular return while keeping the additional revenue, and then returns the farm after this lease period. Supporting multiple business models will require large external investment.

Improve yields and livestock efficiencies in sub-Saharan Africa

Rates of yield gain in sub-Saharan Africa over the last two decades have been slow. In a paper in review, co-authors and I estimate that the region will likely need to convert 450 million hectares of land – a staggering area – to meet food needs in 2050 if present low rates of yield gains continue. Along with higher emissions from the production process, annual emissions by 2050 will rise to 4 or 5 gigatons of carbon dioxide equivalent per year by 2050, which is not compatible with any global solution to climate change.

The same paper finds that the basic ways to mitigate these emissions are essentially the same measures necessary to produce adequate food. They include closing yield gaps, focusing most of the increased livestock production on poultry and dairy rather than beef, and treating crop residues to improve their digestibility for livestock. This last method expands the food supply without using more land.

Although some investments may require private/public partnerships, investors have a key role to play. The most obvious targets for companies are to help farmers revitalize aging and increasingly unproductive coffee and cocoa plantations with new plantings. More broadly, a full world of investments in agricultural infrastructure are required.

Linkage

Although yield gains are indispensable to avoiding land use change, they are not enough. The basic reason is the shifting of agricultural land already discussed. Although this shifting allows some land to reforest and rebuild biodiversity, the costs nearly always exceed the benefits. Habitats are immediately cleared, releasing their carbon and destroying their biodiversity, while older areas regrow only slowly – and in many situations, regrow as forest plantations not natural forests. In addition, the world has been shifting agriculture into more carbon rich, and biodiverse lands in the Tropics in general[36]. Even with yield gains adequate to avoid global agricultural expansion, some of these shifts and resulting losses of carbon and biodiversity are likely to continue. Roadbuilding, which is occurring on a massive scale[37], will play a prominent role. It makes converting forest areas more profitable by lowering the costs of inputs and reducing the cost of transporting agricultural products out.

Of course, tropical countries also have important reasons to preserve their own forests. As only the most prominent example, the Amazon is a critical source of rain for Brazil's agriculture, and its ongoing conversion risks soon turning it into a savanna, destroying this water supply.

One way to promote global investments in improving agricultural productivity is to link them to protection of forests and other natural habitats. In this manner, countries and governments providing this investment can be assured that they achieve the desired climate benefits. Doing so would follow Brazil's own example. It's climate strategies for two decades now, originally released as the "ABC plan," have linked increased government assistance to improving agriculture on existing lands – often through low cost loans – to forest protection[38]. These kinds of investments could build on the concept of "jurisdictional REDD," in which companies or governments pay for avoided deforestation at the level of government jurisdictions. Similar structures might attract international investment.

36 Aide et al. (2013), Johnson et al. (2014)

37 Laurance et al. (2014)

38 Jackson (2015)

Investments in innovation

Addressing the global land use challenge requires investments in innovations both to avoid clearing more land and to reduce the roughly 10% of global emissions that result from the agricultural production process, such as methane and nitrous oxide. The guiding principle might be called high-tech eco-agriculture. Although the breadth of potential innovations is too long for full discussion, a few examples at different stages of development illustrate some possibilities.

- → Biological nitrification inhibition: Nitrogen use in agriculture results in nitrous oxide emissions that warm the planet, as well as extensive water pollution. A necessary contribution to both forms of pollution is the transformation in soils of nitrogen from one form (ammonium) into another (nitrate). A small group of breeders have developed a high-yielding wheat variety and are making progress on other crops, that impede this transformation. Doing so lowers emissions and has the potential to boost yields[39].

- → Turning crop residues into quality animal feeds: Crop residues contain roughly as much energy as crops but are a poor animal feed because they cannot be well digested. Low-tech methods exist to make them more digestible for cattle but have been little adopted. High-tech methods also exist but are presently too expensive. The same pretreatment options to turn residues into ethanol could more cheaply make residues a higher quality feed. These same methods could also allow farmers to switch from annual crops to perennial grasses, with potentially higher yields and lower emissions.

- → Making manure valuable: Methods exist to separate the solids, the water, and the nutrients in manure, allowing each to be well used. Alternatively, microbes may be able to turn manure into a quality animal feed.

Each of these options should not only reduce production emissions and other pollution but also reduce the land area we need for agriculture. The challenge is advancing each technology enough to become cost-effective.

An uncertain market limits investment. Today greenhouse gas savings in agriculture have no reward, so farmers have no reason to adopt them if they cost even one cent more. Governments could encourage investment by promising to require or subsidize innovations that achieve greenhouse gas reductions, including land use savings, if innovations bring down costs to a reasonable level.

39 Subbarao and Searchinger (2021), Subbarao et al. (2021)

Roadmap for future action

The global land squeeze is a fundamental challenge of our time. Solving it is as critical for biodiversity as for carbon[40]. Directing private investment on the right path is critical. Unfortunately, through limited understanding and accounting errors, the challenge is often underestimated, encouraging investments that can exacerbate problems. To address these challenges, investors need to encourage accounting reform to reflect the carbon opportunity cost of land, and to encourage policies that commit to requiring or subsidizing new technologies if they prove cost-effective ways of reducing emissions. They need to invest both in alternatives to beef and to improvements that increase the efficiency of beef production. Investors need to turn attention to Africa. And they need to invest in bold, technological innovations that can both reduce emissions from the production process and use land more efficiently.

A thought experiment guides us on how we should value land. What if the world had a perfect global carbon price, which economists can prove would in theory generate the most efficient solutions to climate change? In such a world, everyone who cleared a hectare of land would pay that carbon price, and everyone who reforested land would be paid. Even at a carbon price of only $100 per ton of carbon dioxide, clearing forests would require payments of $40,000 or so, and reforesting poor grazing land in Latin America might receive a payment of $1,500 per hectare each year. Because land would be so valuable to store carbon, the incentive to use less land by producing more food on the same land would be strong. People and companies would also have a strong incentive to avoid land-inefficient products such as biofuels and beef. Investors, scientists, and governments would turn far more attention to helping farmers to boost their productivity.

Although practical and political reasons prevent this global pricing, the thought experiment reveals how the world should treat land if it wishes to solve climate change. Land is not free. The "carbon opportunity cost" of land needs to be factored into land use decisions, including by investors. Land is a valuable, limited resource that the world needs to use more efficiently both to supply food and to safeguard nature.

40 Balmford et al. (2023)

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